Controlling the Incident Ion Energy at Substrate Surfaces

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ABSTRACT

In plasma processing systems, the magnitude of the incident ion energy at surfaces can be regulated through the use of RF biasing. Increasing the RF power typically increases the average ion energy but also increases the energy spread. Thus, it is difficult to precisely regulate the incident energy. However, the spread in energy is dependent on both the plasma density and the applied RF frequency and so, the energy spread is variable. In this work, we discuss methods for controlling the incident ion energy using electron beam generated plasmas. The results suggest a system capable of producing a well-defined and regulated incident ion energy.

INTRODUCTION

RF biasing of substrates can be used to increase the magnitude of the incident ion energy at surfaces and is often used to achieve certain desirable material attributes in processing applications. Typically, the average energy can be increased by increasing the applied RF power. This is commonly accompanied by an increase in the energy spread. Thus, for applications where precise control of the energy is essential, this approach falls short. However, the spread in energy is dependent on both the plasma density and the applied RF frequency and so by adjusting these parameters, the spread in energy can be minimized.

The Naval Research Laboratory has developed a materials processing system based on electron beam-generated plasmas for use in a range of applications. [1,2] When high-energy (≈ 2 keV) electron beams are used as the primary ionization source, the resultant plasmas have several unique characteristics when compared to conventional low-pressure plasma sources. Relevant to this work are attributes that allow for precise control of the ion energy, including:

Controllable plasma density. In our recently developed CW electron beam source (used in this work), the beam current is easily regulated by varying the source operating conditions, and since the ion generation is directly proportional to the beam current for all gases, the plasma density is easily adjusted. In conventional sources of comparable reactor geometries, the plasma density depends on the working gas and applied power.

Localized plasma source. The plasma production region is limited to the beam volume, which is well defined and uniform when the beam is magnetically collimated. Fields of approximately 150 gauss are sufficient to minimize beam spreading in systems up to 1 m long. Beam thicknesses of 1 cm are typical in these systems. Outside the beam channel, the plasma density is altered by diffusion as well as ion-electron and ion-neutral reactions, so electrodes (or substrates) can be independently positioned to take advantage of the changes in density. This is in contrast to conventional discharges, where the boundaries of the ionization region are not well defined. Thus, it is possible to carefully control the plasma density near adjacent surfaces by moving the surface position [3].

Low electron temperature. The electron temperature T_e determines the presheath voltage drop, which in turn, determines the minimum spread in incident ion energy. This spread (or presheath drop) is approximately equal to $\frac{1}{2}T_e$. Because the high-energy electron beam ionizes the gas and there is no heating applied to the plasma electrons, plasma electrons are rapidly cooled by inelastic collisions (Electrostatic cooling further reduces T_e, especially in noble gases.). In beam produced plasmas, the electron temperature varies with the working gas, but is ≤ 1 eV in all gases. [3,4] In discharges, the electron temperature is typically above 2 eV and so the minimum spread in energy is at least twice that in electron beam generated plasmas.

In combination, these attributes provide not only a smaller inherent spread in energy but also a straightforward way of regulating the system properties so that the plasma density near a surface can be controlled. In this work, we exploit some of these properties to explore the possibility of producing a well-defined and regulated ion energy at surfaces adjacent to electron beam-produced plasmas.

EXPERIMENTAL

The experimental apparatus has been discussed previously [5] and is shown in the schematic of Figure 1. The chamber consists of a 6-way cross (50 cm from flange to flange) attached to a larger cylindrical chamber and the system vacuum was maintained by a 100 l/s diffusion pump, with a base pressure on the order of 10^{-6} Torr. The operating pressure

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was achieved by introducing high-purity gases through mass flow controllers and throttling the diffusion pump using a manual gate valve.

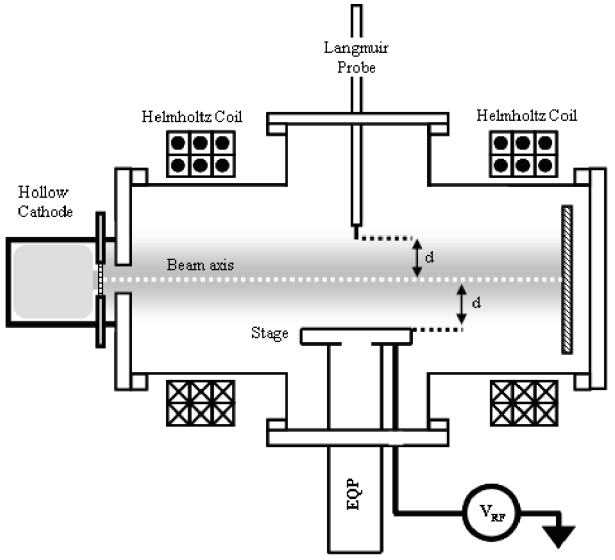

Figure 1: A schematic diagram of the processing system.

The electron beam source uses a hollow cathode as an electron source and a high voltage grid to accelerate those electrons to form an energetic beam of electrons. The DC discharge in the hollow cathode produces a plasma and the plasma electrons are extracted through wire-grid anode and then accelerated by the grid potential. The hollow cathode discharge thus determines the beam current, while the accelerating voltage determines the beam energy. The hollow cathode operates at a few hundred volts with respect to a wire-grid anode, which in turn, is held at thousands of volts (up to -5 kV) with respect to ground. The wire-mesh anode is 1 cm wide by 10 cm long and it consists of stainless steel mesh with openings of 60 x 60 µm and a 30 % transmission. The ground anode also has a 1 x 10 cm opening. All parts are stainless steel and isolated from one another by ceramic spacers.

The Langmuir probe was constructed from ceramic and stainless steel tubes. The tip was a loop of tungsten wire with an exposed area of 2.5 x 10^{-3} cm^2. The probe was heated at a constant current of 2.5 A to prevent oxidation and contamination of the tungsten. A LabVIEW™ program [6] was used to control the bias source (Stanford Research SR245, Keithley 2400) and to perform the data analysis. IV traces were produced and a data analysis routine was used to determine the plasma electron temperature (T_e), the plasma potential (V_p), the floating potential (V_f) and the electron density (n_e). No allowance was made for the beam current because the beam density was much smaller than the plasma density in all experiments.

The ion flux was measured at the center of a 5.7 cm diameter, stainless steel electrode using a Hiden EQP 300 Plasma Probe, located approximately 1 cm from the electron beam edge. Species enter the EQP through a 50 µm diameter aperture located in the center of the electrode and are first energy selected by an electrostatic energy analyzer and then mass filtered by a quadrupole mass spectrometer. The energy analyzer has a fixed resolution that provides an uncertainty in energy of approximately ± 0.15 eV. The EQP has not been calibrated to determine the absolute flux of each species, so the intensity of the measured signal is reported in arbitrary units.

Biasing of the electrode was accomplished using a variable frequency RF generator, which was delivered through an RF amplifier.

RESULTS AND DISCUSSION

Spatial distributions of the electron temperature and plasma density in a plasma produced in pure argon are shown in Figure 2. The estimated plasma potential for argon was 2.6 V. The pressure in the chamber was 20 mTorr. The grid voltage was 1.3 kV and the beam current was approximately 19 mA. The hollow cathode voltage and current were 360 V and 35 mA. The magnetic field strength was 100 G. The electron temperature was 0.45 eV and was approximately constant inside the beam (the variation was less than 10 %) but then fell to 0.35 eV outside the beam. By contrast, the plasma density changed by an order of magnitude (from 2.3 x 10^{11} cm^{-3} in the middle of the beam to 2.2 x 10^{10} cm^{-3} outside the beam).

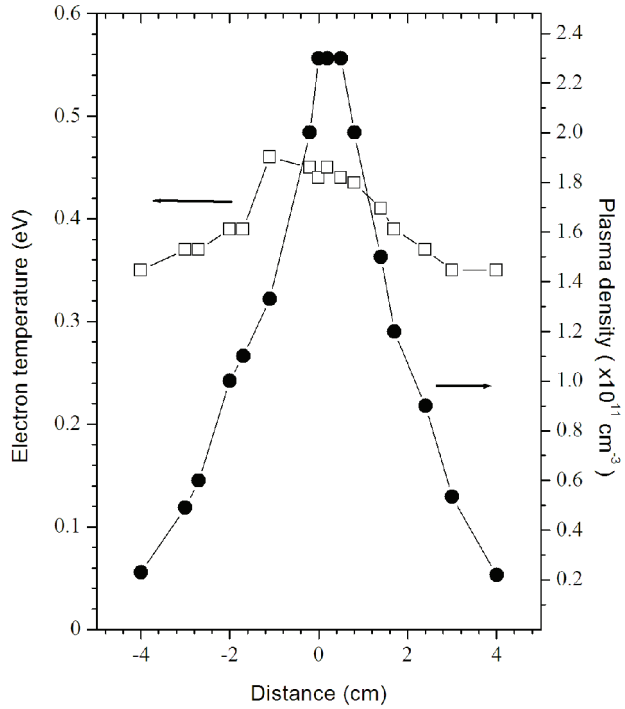

Figure 2.: Electron temperature and plasma density as a function of position. Zero is taken to be the center of the electron beam.

The effect of the hollow cathode voltage on the electron temperature and plasma density is presented in Figure 3. The measurements were performed in an argon-nitrogen mixture (93 % Ar/ 7 % N_2). In this experiment the pressure was 50 mTorr, the grid and hollow cathode voltages were 0.8 kV and 280 V respectively. The magnetic field strength was 130 G. As the hollow cathode current increased from 40 mA to 120 mA, the plasma density increased two-fold, from 3 x 10^{11} cm^{-3} to 7 x 10^{11} cm^{-3}. The electron temperature also changed slightly from 0.4 eV to 0.5 eV.

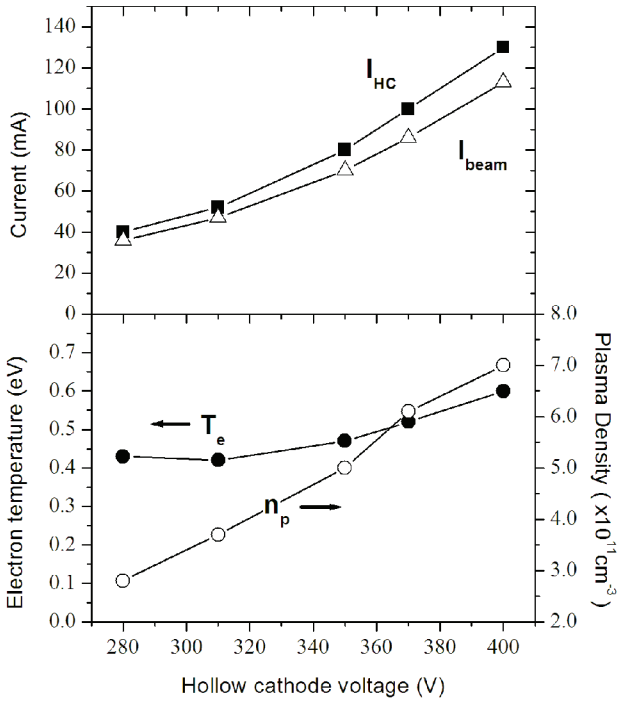

Figure 3: (a) The hollow cathode current and approximate beam current and (b) the electron temperature and plasma density as a function of the hollow cathode voltage.

Shown in Figure 4 are the ion energy distributions measured at an electrode biased using a constant rf power for several different beam currents and thus different plasma densities. Here, the breadth of the distribution changes as a function of the plasma density. Generally, as the density increases, the breadth increases. Note the difference in structure for each ion species.

Shown in Figure 5 are the Ar^{+2} ion energy distributions using a variable rf driving frequency at two different plasma densities. Here again, the breadth of the distribution changes. In this case, as the driving frequency increases, the breadth decreases.

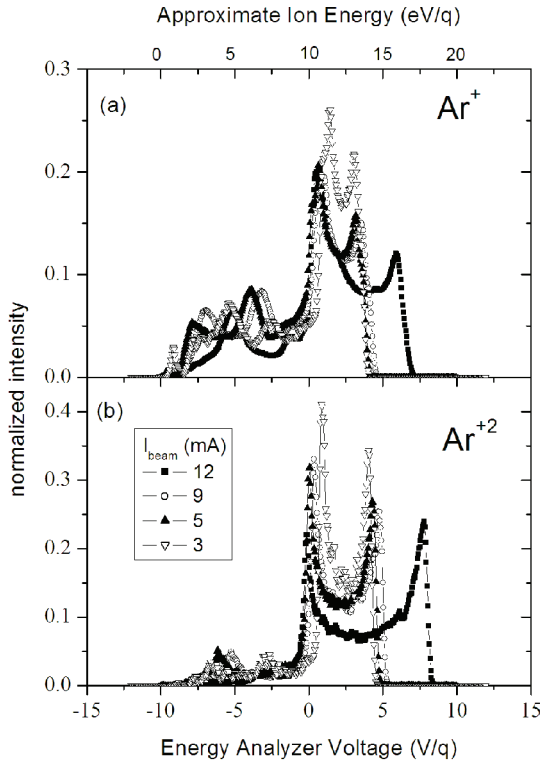

Figure 4: Ar^+ and Ar^{+2} ion energy distributions as a function of approximate beam current measured at an rf biased (13.56 MHz) electrode.

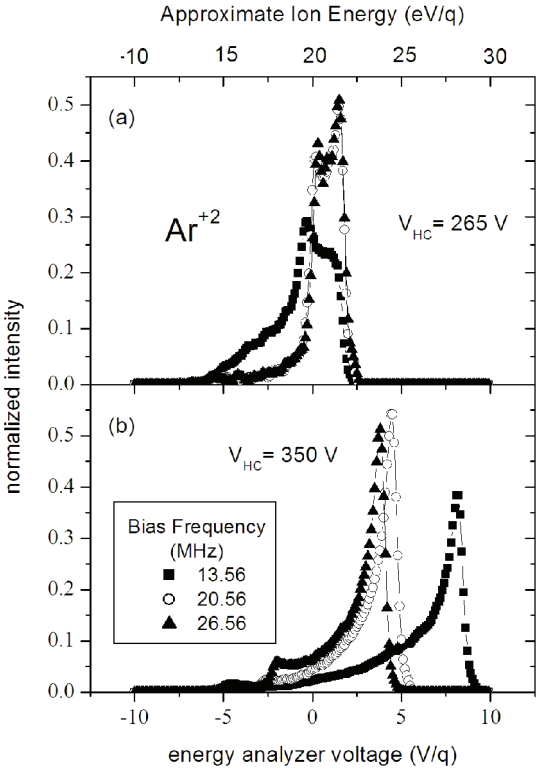

Figure 5: Ar^{+2} ion energy distributions as a function of the rf bias frequency using both (a) low and (b) high beam current density.

If the ion transit time across the sheath (τ_{ion}) is much greater than the applied rf frequency period (τ_{rf}), then the ions respond only to the average sheath voltage (V_{sb}) and under these conditions, the spread in the ion energy distribution can be expressed as, [7]

$$\Delta E = (3/\pi) e V_{sb} (\tau_{rf} / \tau_{ion}) \quad (1)$$

The transit time may be reasonably approximated using the ion plasma frequency (ω_{ion}),[7] which in turn is proportional to the plasma density(n_p),

$$\tau_{ion} = 1/\omega_{ion} = (4\pi z^2 q^2 n_p / M)^{-1/2} \quad (2)$$

In noble gases like argon, the plasma density n_p is directly proportional to the beam current I_b, and therefore ΔE varies as,

$$\Delta E = E_{ion} (I_b)^{1/2} \Big/ \omega_{rf} \quad (3)$$

These relationships only hold if the sheath is collisionless: that is, the sheath thickness, s, is greater than the mean free path, λ. Given the multimodal structure observed in the Ar^+ ion energy distributions (Figure 4), it assumed that the sheath can only be considered collisionless for the Ar^{+2} ions. Using the relationship for ΔE above, we can estimate the spread in energies and the results are shown in Figure 6.

The predicted values generally follow the same trend as measured values. However, they overestimate the spreads in energy and this may be related to the fact that we have assumed the transit time is much greater than the rf period, which may not hold under these operating conditions. Nonetheless, the results demonstrate it is possible to narrow the ion energy distributions, which allows better control over the incident ion energy.

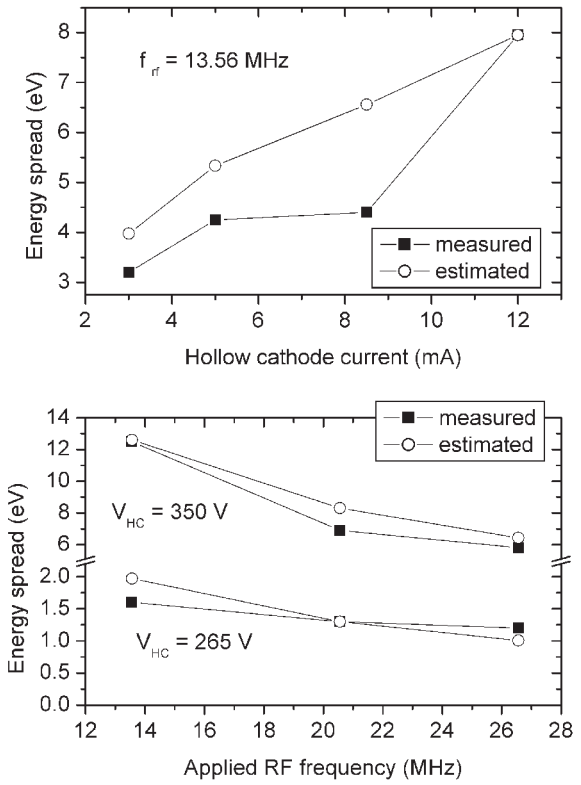

Figure 6: The measured and estimated spread in Ar^{+2} ion energy distributions for (a) variable beam currents at constant rf bias frequency and (b) variable rf bias frequency at high and low beam current density.

CONCLUSION

Experiments designed to regulate the incident ion energies in electron beam generated plasmas were discussed. The results show it is possible to elevate the incident ion energies and also narrow the spreads in energy. These results indicate the possibility of processing with a well-defined and controlled incident ion energy. The ultimate goal is a selectable and nearly mono-energetic incident ion energy. In order to achieve this, it appears a combination of lower plasma density and higher driving frequency is required.

ACKNOWLEDGEMENTS

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